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Mass extinctions and supernova explosions

PAUL J. CRUTZEN AND CHRISTOPH BRÜHL

Max Planck Institute for Chemistry, P.O. Box 3060, 55020 Mainz, Germany

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ABSTRACT **In a recent contribution to this journal Ellis and Schramm [Ellis, J. & Schramm, D. N. (1995) *Proc. Natl. Acad. Sci. USA* 92, 235–238] claim that supernova explosions can cause massive biological extinctions as a result of strongly enhanced stratospheric NO_x ($NO + NO_2$) production by accompanying galactic cosmic rays. They suggested that these NO_x productions which would last over several centuries and occur once every few hundred million years would result in ozone depletions of about 95%, leading to vastly increased levels of biologically damaging solar ultraviolet radiation. Our detailed model calculations show, however, substantially smaller ozone depletions ranging from at most 60% at high latitudes to below 20% at the equator.**

Ellis and Schramm (1) claim that nearby supernova explosions might have caused one or more of the mass extinctions identified by paleontologists by depleting the atmospheric ozone layer, thereby exposing organisms to potentially lethal solar UV irradiation. The discussion by Ellis and Schramm (1) is based on a number of simplifying assumptions and use of a formula going back to the first study on the topic by Ruderman (2), which in turn was based on studies about the effects of NO_x ($NO + NO_2$) additions to the stratosphere in the early 1970s. In this formula, independent of altitude, the ratio of the perturbed to unperturbed ozone concentrations, F, to the corresponding ratio X of NO_x ($NO + NO_2$) is given by

$$F = [(16 + 9X^2)^{1/2} - 3X]/2. \quad [1]$$

Ruderman (2) claimed this expression to be an "idealization of the chemical kinetics which also gives a rough fit to numerical calculations."

Because the catalytic destruction of ozone by NO_x via the pair of reactions (3)

$$NO + O_3 \rightarrow NO_2 + O_2 \quad [R1]$$

and

$$O + NO_2 \rightarrow NO + O_2 \quad [R2]$$

is particularly dependent on the concentrations of oxygen atoms which are produced by photolysis of O_3

$$O_3 + h\nu \rightarrow O + O_2 \quad [R3]$$

and removed via

$$O + O_2 + M \rightarrow O_3 + M, \quad [R4]$$

(M, arbitrary air molecule) the ozone destruction efficiency falls off rapidly toward lower altitudes, an effect which is not considered in Eq. 1. Also it appears that Eq. 1 was derived for relatively small deviations from the normal chemical state of the stratosphere, casting doubt on its applicability for situations with much larger values of X. In addition, research has shown that in the altitude range below about 25 km conversion of the NO_x catalysts to HNO_3 is substantially enhanced by the reaction of NO_x-derived N_2O_5 with H_2O on stratospheric sulfate aerosol:

$$N_2O_5 + H_2O \rightarrow 2HNO_3 \quad [R5]$$

Furthermore, it was shown in 1978 that the reaction

$$HO_2 + NO \rightarrow OH + NO_2, \quad [R6]$$

which leads to ozone production in the lower stratosphere, proceeds about 40 times faster than earlier measurements had indicated (4), thereby considerably reducing NO_x-catalyzed ozone destruction. For a number of reasons Eq. 1 strongly overestimates ozone depletions resulting from NO_x additions to the stratosphere.

It is the aim of this study to present the results of a less parametric treatment of the issue, using an up-to-date, com-

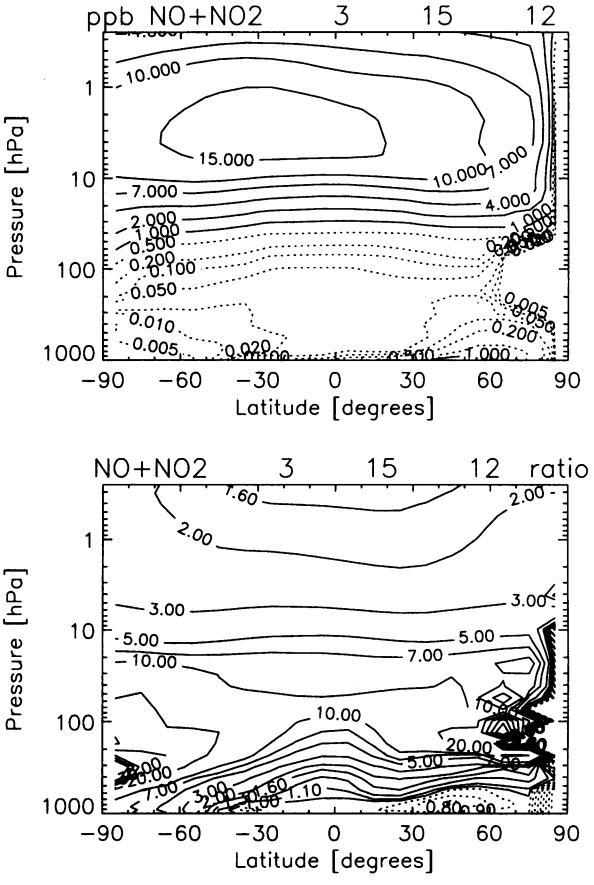

FIG. 1. Calculated meridional cross section of NO_x volume-mixing ratios in ppb (10^{-9}) by volume for the present (*Upper*) and upper limits for the supernova-disturbed atmosphere (*Lower*) given as ratios to the present (for mid-March).

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Abbreviation: GCR, galactic cosmic rays.

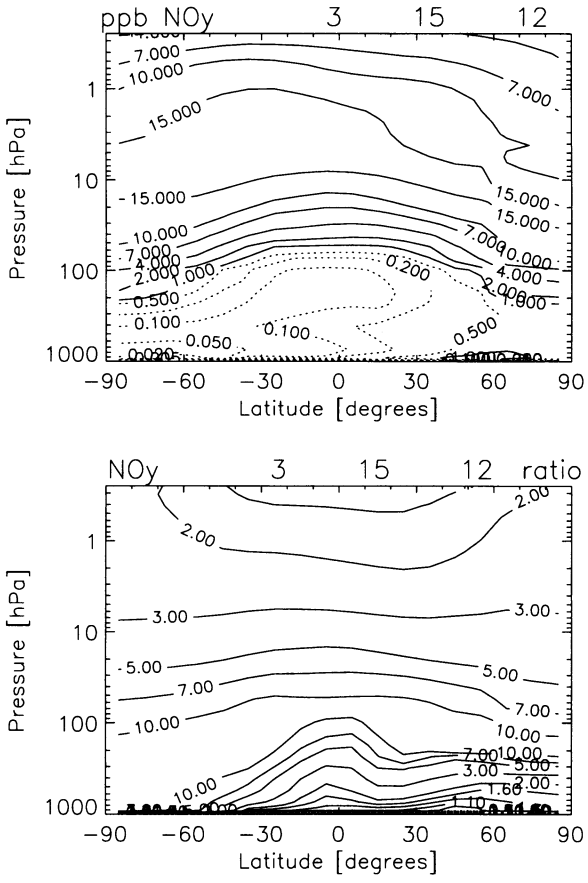

FIG. 2. Same as Fig. 1, but for all odd nitrogen compounds (NO_x + NO_3 + $2N_2O_5$ + HNO_3).

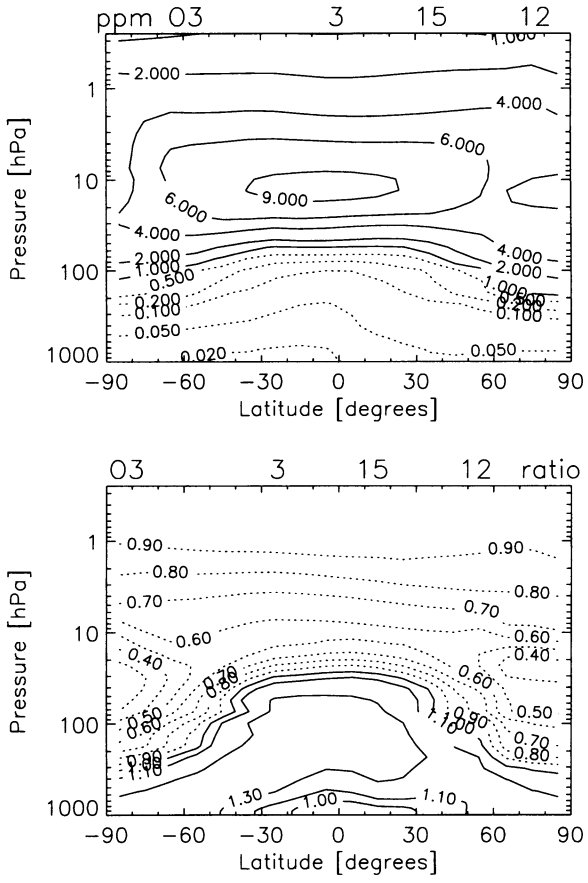

FIG. 3. Calculated meridional cross sections of ozone volume-mixing ratios in ppm (10^{-6}) by volume for mid-March. (*Upper*) Present atmosphere. (*Lower*) Minimum possible values for a supernova-disturbed atmosphere (presented as ratios to the present).

prehensive, two-dimensional, height-, latitude-, and time-dependent model of stratospheric chemistry with a complete set of reactions representing currently known chemistry and reaction rates (5, 6). Otherwise, in this study we will hold ourselves as closely as possible to the numerical assumptions in the paper by Ellis and Schramm (1).

NO is formed by the action of galactic cosmic rays (GCR) on N_2 and O_2, leading in particular to the production of N atoms in their ground (^4S) and electronically excited states (^2D or ^2P). Following rapid reaction with O_2, the excited states always produce NO. However, as the reaction between ground state N and O_2 is rather slow, the "cannibalistic" reaction

$$N + NO \rightarrow N_2 + O \qquad \textbf{[R7]}$$

limits the amount of NO that can accumulate in the stratosphere. The actual production of NO is thus significantly smaller than the production of N atoms by the GCR. This fact was indeed considered by Ellis and Schramm (1), based on the formula derived earlier by Ruderman (2). In fact, as almost all NO production takes place at high geomagnetic latitudes (>60°) the formula of Ruderman (2) overestimates the loss of NO_x by neglecting the absence of reaction **R7** during polar-night conditions, when NO is converted to NO_2 and higher oxides of nitrogen, in which case the N atoms mostly react with O_2 to produce NO.

To obtain an upper limit estimate of the ozone loss by a supernova, we assume that actual NO deposition in the atmosphere equals total N production by GCR. Following Ellis and Schramm (1), the stratospheric NO production rate over a period of 300 years would then be almost 100 times larger than the current rate of NO production by GCR—i.e., globally averaged, 10^9 molecules·cm^{-2}·s^{-1}. This NO is, however, largely deposited at geomagnetic latitudes higher than about 60° (7), which, therefore, experience a production flux of 6×10^9 molecules·cm^{-2}·s^{-1} lasting for about 300 years (1). At lower latitudes, the areal deposition densities, although appreciably smaller, are still significant. The NO flux is introduced in our two-dimensional model as a function of latitude and altitude according to a figure given in Brasseur and Solomon (7) and using further data of Nicolet (8). Calculated meridional cross sections of NO_x volume ratios for the present and the supernova disturbed atmosphere for mid-March are presented in Fig. 1, showing up to a 20-fold increase in NO_x mixing ratios near 100 hPa at high latitudes and less elsewhere. The corresponding enhancements for all odd nitrogen compounds [NO_y = NO_x + NO_3 + $2N_2O_5$ + HNO_3] is shown in Fig. 2. Comparison between Figs. 1 and 2 shows that below 5 hPa (≈35 km) a large fraction of the odd nitrogen is present as compounds other than chemically active NO_x, despite their initial inputs as NO in the model. The globally averaged upper limit of NO production of 3.2×10^9 molecules·cm^{-2}·s^{-1} by supernova GCR is about 100 times larger than the NO production by normal GCR and 20 times larger than the main source of stratospheric NO_x provided by the oxidation of N_2O (9). More than half of the NO production by GCR occurs below the 100 hPa level.

In Fig. 3 we present the meridional ozone distribution calculated for mid-March in the present atmosphere and the relative percent reductions in an atmosphere bombarded by the supernova GCR. We calculate depletions in ozone concentrations up to 70% at high latitudes in the stratosphere. The corresponding total ozone changes, shown in Fig. 4, also maximize at high latitudes reaching 50% in the summer season.

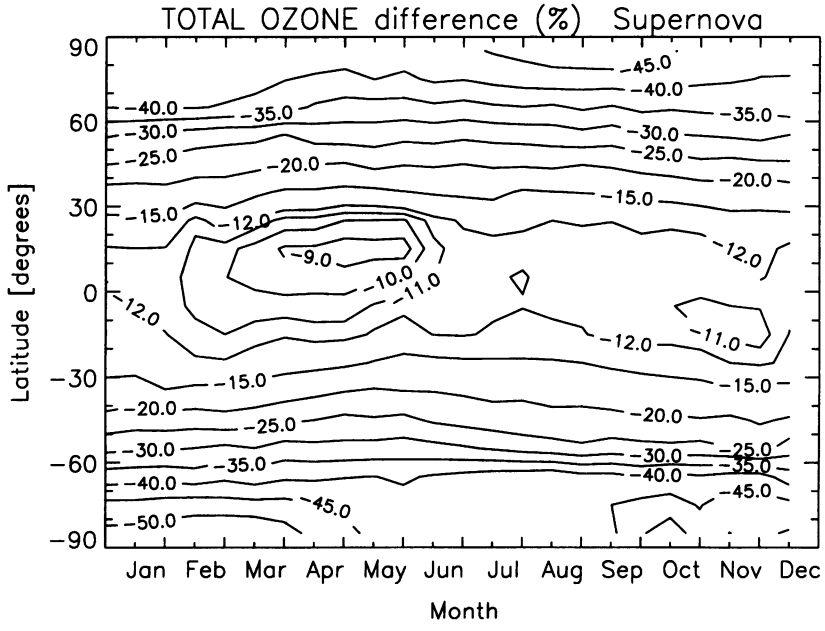

FIG. 4. Seasonal and latitudinal distributions of the upper limits of relative total ozone changes (in %) between the present and a supernova-disturbed atmosphere.

In the tropics, total ozone is depleted by 10–20%. We repeat that the calculated ozone depletions are overexaggerated due to the neglect of NO destruction by reaction **R7**, which will be important during sunlit, summer-time conditions.

Our model results on ozone depletions are much smaller than the 95% reduction estimated by Ellis and Schramm (1) on the basis of Eq. **1**. For the tropics, total ozone loss was calculated to be ≈15%. Although significant stress may well have been exerted on the high latitude biosphere, the effects on the tropical and subtropical biosphere may not have been strong enough to cause mass extinctions. Large ozone depletions at low latitudes would only be possible if the earth's magnetic field would be much disturbed, allowing much more GCR to reach lower latitudes, as is the case during magnetic reversals (10). The likelihood for a supernova event to coincide with a geomagnetic reversal is, of course, very small.

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